Mad Dog TTI RTM: Better than Expected
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Summary

In 2009, BP initiated a complete reprocessing of the Mad Dog WATS (wide-azimuth towed-streamer) dataset using TTI (tilted transverse isotropy) Pre-stack Depth Migration (PSDM) technology developed by CGGVeritas. This project would build upon the 2008 VTI (vertical transverse isotropy) model built by CGGVeritas by improving key areas that were imaged poorly. The TTI reprocessing was extremely successful. In fact, the uplift for the subsalt target area was qualitatively larger than the uplift observed between isotropic and VTI. Mad Dog TTI reprocessing further confirmed that by honoring the stratigraphic layering of the geologic structure, a TTI velocity model is a better approximation of the subsurface than both isotropic and VTI models. The Mad Dog WATS data combined with a previously recorded NATS (narrow azimuth tow streamer) dataset allowed the ability to detect and account for anisotropy in different azimuths, which is not possible with a single NATS survey. TTI reverse time migration (RTM) improved the ability to define salt geometry and thereby obtain a good subsalt image. TTI RTM should be considered for future imaging of fields with complex structures such as Mad Dog.

Introduction

The Mad Dog field, the third giant field in BP’s Gulf of Mexico (GOM) portfolio, is about 140 miles south of the Louisiana coastline in the southern Green Canyon area within the Atwater (Mississippi Fan) fold belt (Figure 1). It was discovered by BP in November 1998 and started producing in 2005. The field lies in a complex geologic environment on the edge of the Sigsbee Escarpment with most of the reservoir structure underneath the salt canopy and a large mini-basin to the North. Since its discovery, BP has continuously worked on the Mad Dog field with imaging techniques and new acquisition trying to improve the seismic imaging quality in the subsalt region to aid its future development. The major breakthrough came in 2004 when BP began the industry’s first WATS acquisition at Mad Dog. Figure 1 shows the acquisition geometry. The sail line spacing is 250m. The noise reduction from strong stacking power and the better sub-surface illumination (Regone, 2006) enabled WATS to produce better subsalt images: even a brute WATS migration using raw field data and existing velocity model yielded a cleaner subsalt image than fully processed NATS data (Michell et al., 2007).

Around the same time, anisotropic imaging and specifically TTI RTM, began to gain momentum in imaging of deep water GOM fields. People began to realize the importance of anisotropy and its impact on defining salt geometry and subsequent subsalt imaging, as well as imaging next to and underneath salt-withdrawn mini-basins (Huang et al., 2008; Huang and Yu, 2009). The RTM algorithm has no dip limitation and handles all complex waves (Zhang and Zhang, 2008), however is computational intensive and was until recently only used to solve specific problems. Faster computer speeds have made it possible to use RTM more intensively in the velocity model building stages to better define salt geometry (Reasnor et al, 2009). RTM was used at every stage of the Mad Dog TTI salt model rebuild for salt interpretation.

Despite having built a very good VTI Model in 2008, further investigation showed there was a curvature discrepancy on common image gathers (CIG) along different azimuths indicating that the final VTI velocity model was still inadequate (Reasnor et al., 2009). Based on tests from Huang et al. (2008), TTI velocity models, can resolve this kind of discrepancy by honoring background geology structure with dip angle and azimuth angle fields and also produce a simpler and smoother velocity field at the bottom of salt-withdrawn mini-basins. Initial tests (Reasnor et al., 2009) confirmed that a TTI velocity model
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can further improve the subsalt image for the Mad Dog field. In mid 2009, BP decided to rebuild the salt/velocity model for the Mad Dog area utilizing newly developed TTI PSDM technology to improve the overall image quality and support future field development.

TTI Velocity Model Building

Overall, the workflow was similar to that of the Mad Dog VTI imaging project, except this time RTM was used in every major model building step for salt interpretation starting from the sediment flood. The Mad Dog TTI imaging effort also incorporated a NATS dataset that was oriented 66° from the WATS sail direction to better define the anisotropy parameters and assist with water column statics.

The initial TTI vertical velocity, \( V_0 \), was obtained by smoothing the final 2008 VTI sedimentary velocity. The anisotropy parameters \( \delta \) and \( \varepsilon \) (Thomsen, 1986) were calibrated at various well locations. Small lateral variations of \( \delta \) and \( \varepsilon \) were introduced during the fine tuning, but these were still very close to the \( \delta \) and \( \varepsilon \) fields used in the VTI project. The initial dip angle field \( \theta \) and azimuth angle field \( \varphi \) were estimated based on a VTI volume migrated using the initial \( V_0 \), \( \delta \) and \( \varepsilon \). The angle fields were updated after each tomography iteration. A total of four iterations of global WATS tomography update were carried out before the sedimentary flood. Tomography updates were on \( V_0 \) only and were checked against the check-shot profiles and well markers after each iteration to make sure the updates were in the right direction.

Figure 2 shows the butterfly CIG comparison at the center of a salt-withdrawn mini-basin. The events shown are flat, but with dipping overburden. Even though the dipping angle is not big (the dipping angle of salt flank is about 45°), a curvature discrepancy exists between the 66° and 10° azimuths in the VTI CIGs. For this particular location, events from 66° are curving down, and those from 10° are curving up. In contrast, TTI resolved the discrepancy and flattened events along both 66° and 10° azimuths.

Top-of-salt (TOS) and base-of-salt (BOS) showed improvements in both mis-tie and coherency of events. For example, the difference between well marker and seismic event for TOS was reduced to less than 50 feet in the TTI model whereas the average mis-tie in the VTI model is approximately 100 feet (Figure 3). Tomography improved the coherency of events. The coherency of high dip salt flanks adjacent to mini-basins was most impacted by the improved model. Lateral shifts on high dip salt flanks up to 1000 ft were also observed in going from a VTI to TTI model.

The better positioning of TOS is further confirmed by the more coherent BOS event observed in the salt model migrations and final VTI and TTI RTM images (Figure 4). The image shown here is parallel to the salt edge and located at the bottom of a salt keel (image along dipping direction is shown in Figure 5). While VTI final RTM produced a poor BOS image underneath this high dip salt flank, the TTI final RTM yielded much better results: the BOS is more continuous across the whole section, with strong amplitude and sharper focusing. Further image enhancement can be observed in the subsalt image area along the dipping direction near the target area (Figure 5). With a more accurate sediment velocity field, better salt
definition and positioning, TTI yielded a subsalt image with greater continuity of primary events and reduced noise. The removal of the high dip noise resulted in improved fault definition around the target area and the ability to track subsalt events across the whole section.

Figure 3: Absolute Top of Salt (TOS) marker mis-tie (unit feet) comparison between VTI (red bar) and TTI (blue bar).

Conclusions

The Mad Dog image is perhaps one of the better imaged subsalt fields in the Gulf of Mexico. New acquisition strategies (WATS) and new imaging technologies (TTI RTM) have been used to drive image quality which in turn will have a direct impact on field development.

The additional azimuths provided by a WATS survey have impacted the ability to quantify TTI anisotropy. TTI model building has provided flatter events in butterfly CIGs over the VTI model where strong anisotropy exists. All of this in turn leads to better defined salt events and an overall better velocity model. By letting the orientation of the anisotropic symmetry axis vary with structural dip, TTI positions the TOS more accurately which then leads to a better BOS image. Additionally, allowing for TTI produces a simpler and smoother velocity field at the deeper part of salt-withdrawn mini-basins. The better salt geometry and smoother sediment velocity field together yield a much better subsalt image. In the process of building the TTI model well mis-ties for TOS events were reduced from an average of 100 ft in to less than 50 ft.

Figure 4: BOS improvement from TTI. Top panel shows VTI final RTM, bottom panel shows TTI final RTM. Yellow Line shows location of Figure 5.

TTI velocity model building together with TTI RTM has helped change the structural interpretation for key areas by reducing the uncertainty of salt geometry. The impact of TTI could be significant for other basins similar to Mad Dog where mini-basins have moderate dip and very gentle (<20 degrees) subsalt dips. The combination of a WATS style of seismic data acquisition, TTI velocity model building and TTI RTM should be a promising package for future imaging of complex subsalt fields such as Mad Dog.

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